Ceramics

Presented by

Matt Ferber
Oak Ridge National Laboratory

Peer Review of the Microturbine and Industrial Gas Turbine Programs
March 12-14, 2002
Hyatt Fair Lakes, Fairfax, VA

The Team

- **DoE Laboratories (and Subcontractors)**
  - Mechanical Characterization: H-T. Lin, M. Ferber, R. Wills, and J. P. Singh
  - Environmental Barrier Coating Development: R. Lowden, A. Haynes, S. Nunn and B. Armstrong
  - Oxidation/Corrosion Testing: K. More, P. Torterelli, and J. Keiser
  - Non-Destructive Evaluation: B. Ellingson
  - Life Prediction Methodology: S. Duffy
  - Needs Assessment: D. Carruthers

- **Microturbine Companies**
  - B. Schenk: *Honeywell*
  - C. Johnson and R. Sarrafi-Nour: *GE*
  - J. Kesseli: *Ingersoll-Rand*
  - W. Matthews: *Capstone*
  - G. Linsey, G. Ojard, H. Eaton, J. Holowczak, and E. Sun-*UT*

The Team Continued

- **Material Suppliers**
  - Kyocera
  - Honeywell
  - Saint-Gobain Ceramics & Plastics
  - Exothermics
  - Kennemetal

- **Other Turbine Companies**
  - F. Macri and B. Westphal: *Rolls Royce*
  - M. van Roode, J. Price, and N. Miriyala: *Solar Turbines*

Database and Life Prediction

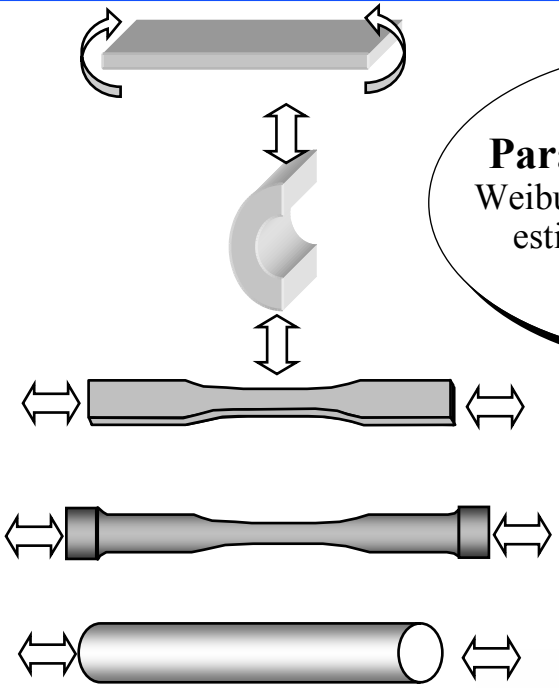
List of Accomplishments
Database and Life Prediction

- **Established extensive data sets for silicon nitride and silicon carbide ceramics of interest to the microturbine community. These data sets, which are in the form of electron spreadsheets, have now been supplied to UTRC, GE, Ingersoll-Rand, and Capstone**
  - Resulting information is required for preliminary materials selection as well as life-prediction studies

- **Based upon these collaborations we have identified other candidate ceramics to include in the database**
  - Have worked with ceramic suppliers including Saint-Gobain, Kennametal, and Exothermics to identify promising materials and to implement characterization studies of those materials

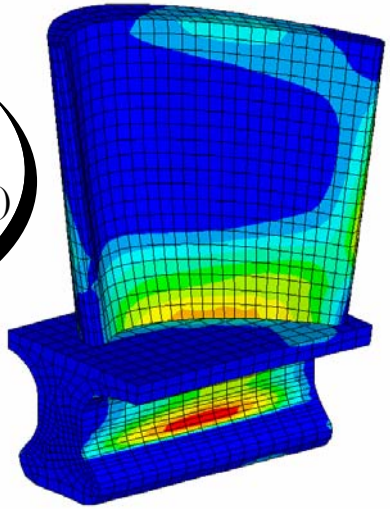
- **Recently we have modified existing tensile frames to allow for tensile testing in a water vapor environment. This facility will be used to evaluate the effect of water vapor upon the mechanical reliability of both uncoated and coated Environmental Barrier Coatings (EBCs)**

Life Prediction Analysis Requires Mechanical Property Data

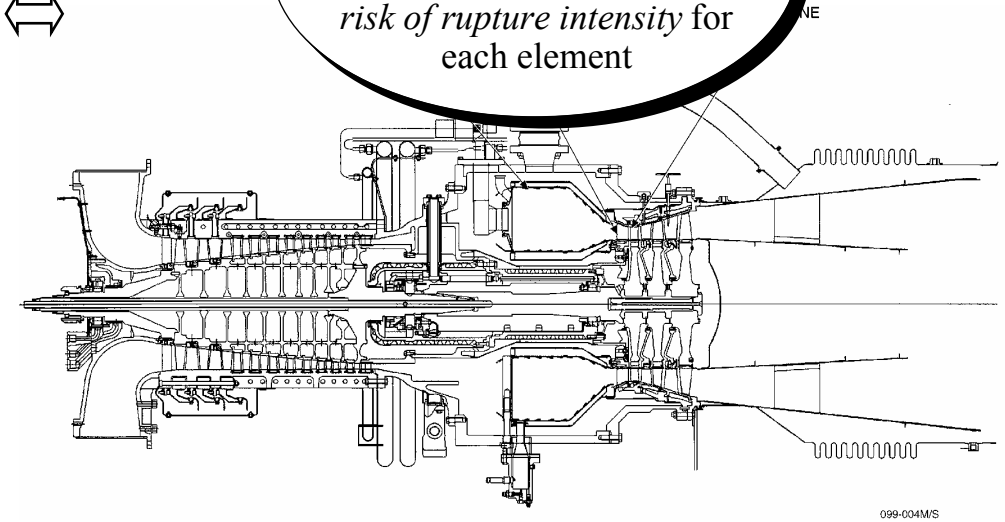


Parameter Estimation
Weibull and fatigue parameter estimates generated from failure data

Finite Element Interface
Output from FEA codes (stresses, temperatures, volumes) read and printed to Neutral Data Base



Reliability Evaluation
Component reliability analysis determines Òhot spotsÓand the *risk of rupture intensity* for each element

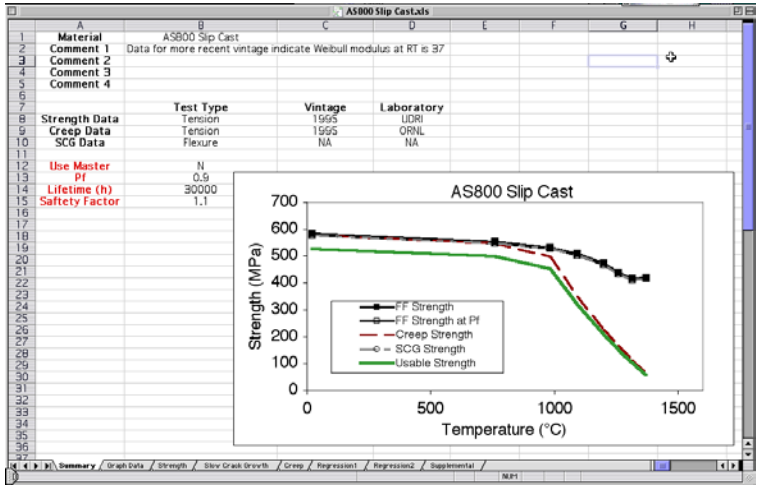


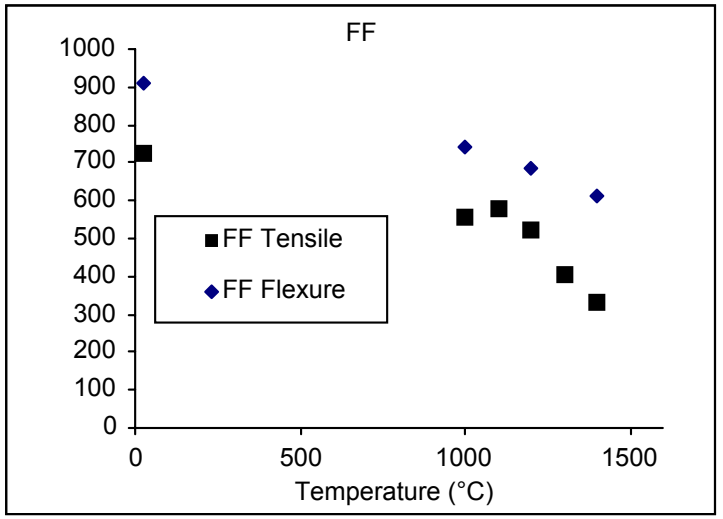
099-004M/S

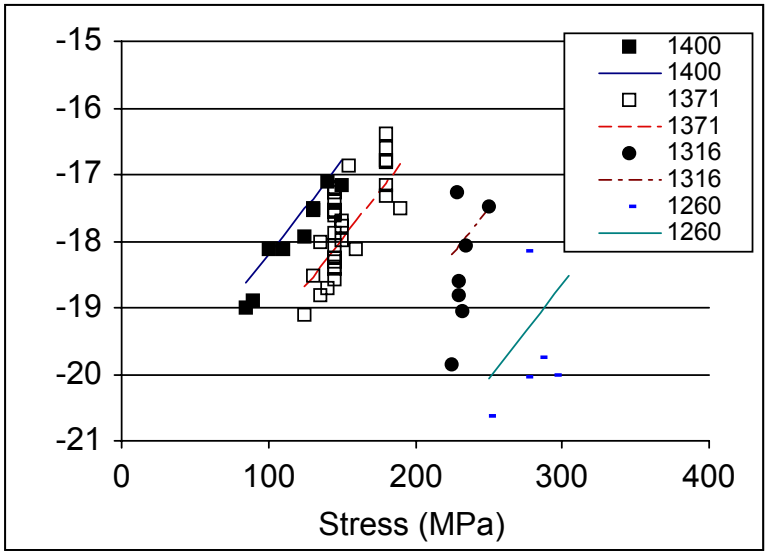
Original Project Goals Focused on Generating These Data

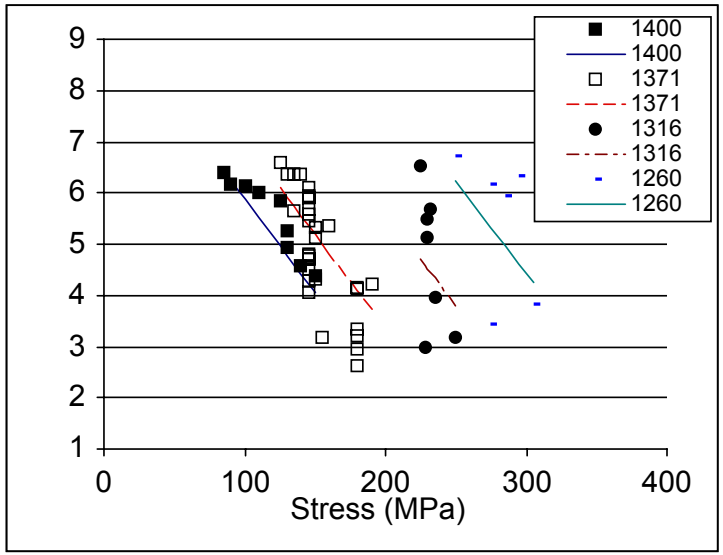
- **Develop Hardware And Methodologies Required To Generate Valid Mechanical Property Data For Design Purposes**
- **Develop Baseline Design Data For Monolithic Ceramics And Ceramic Matrix Composite**
  - Fast Fracture
  - Stress Rupture And Cyclic Fatigue
  - Evaluate Environmental Effects
- **Generate a User-Friendly Database**
- **Evaluate New Materials**

Data for Selected Materials are Currently being Compiled into Excel Workbooks

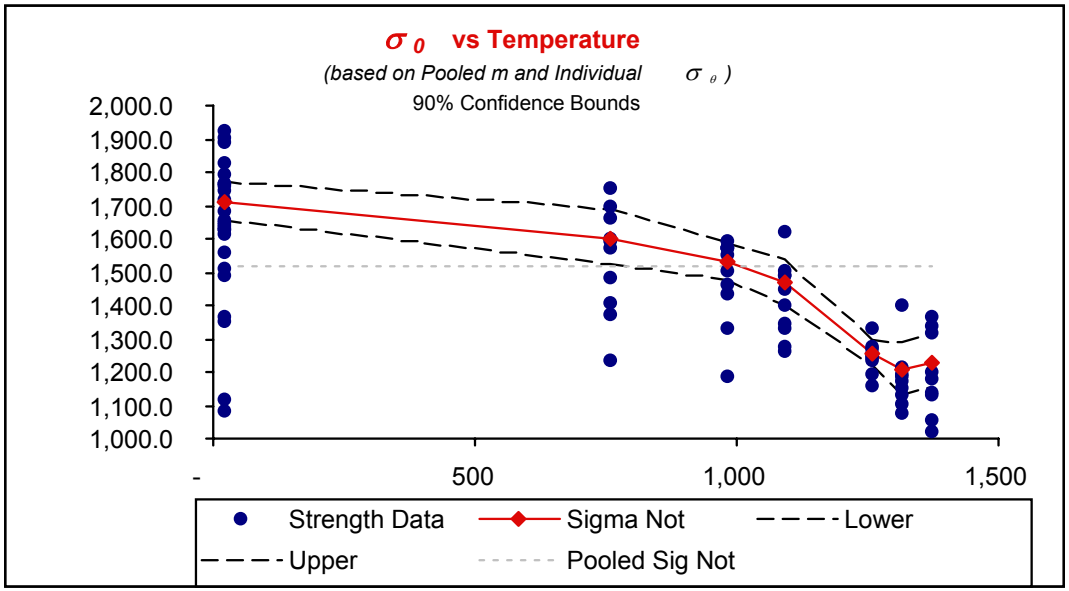


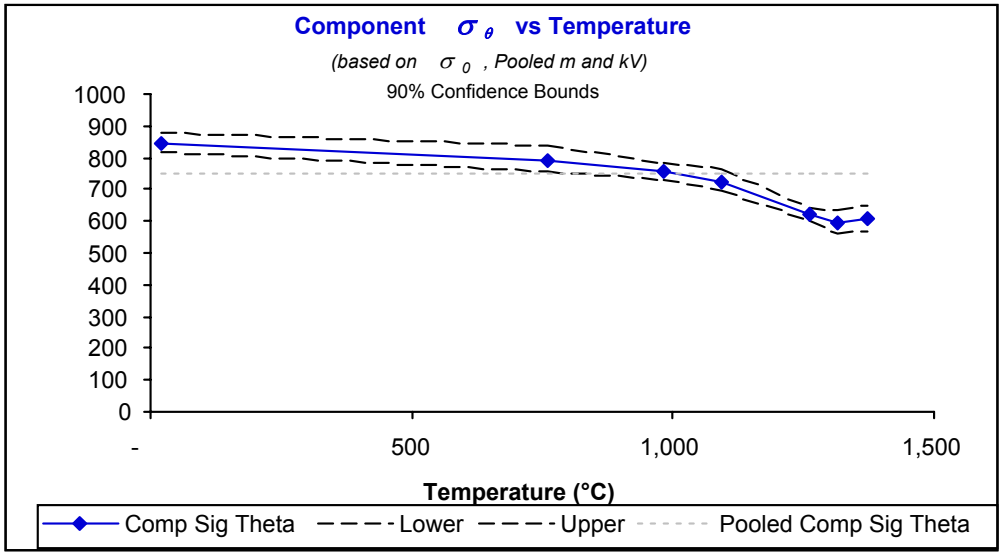




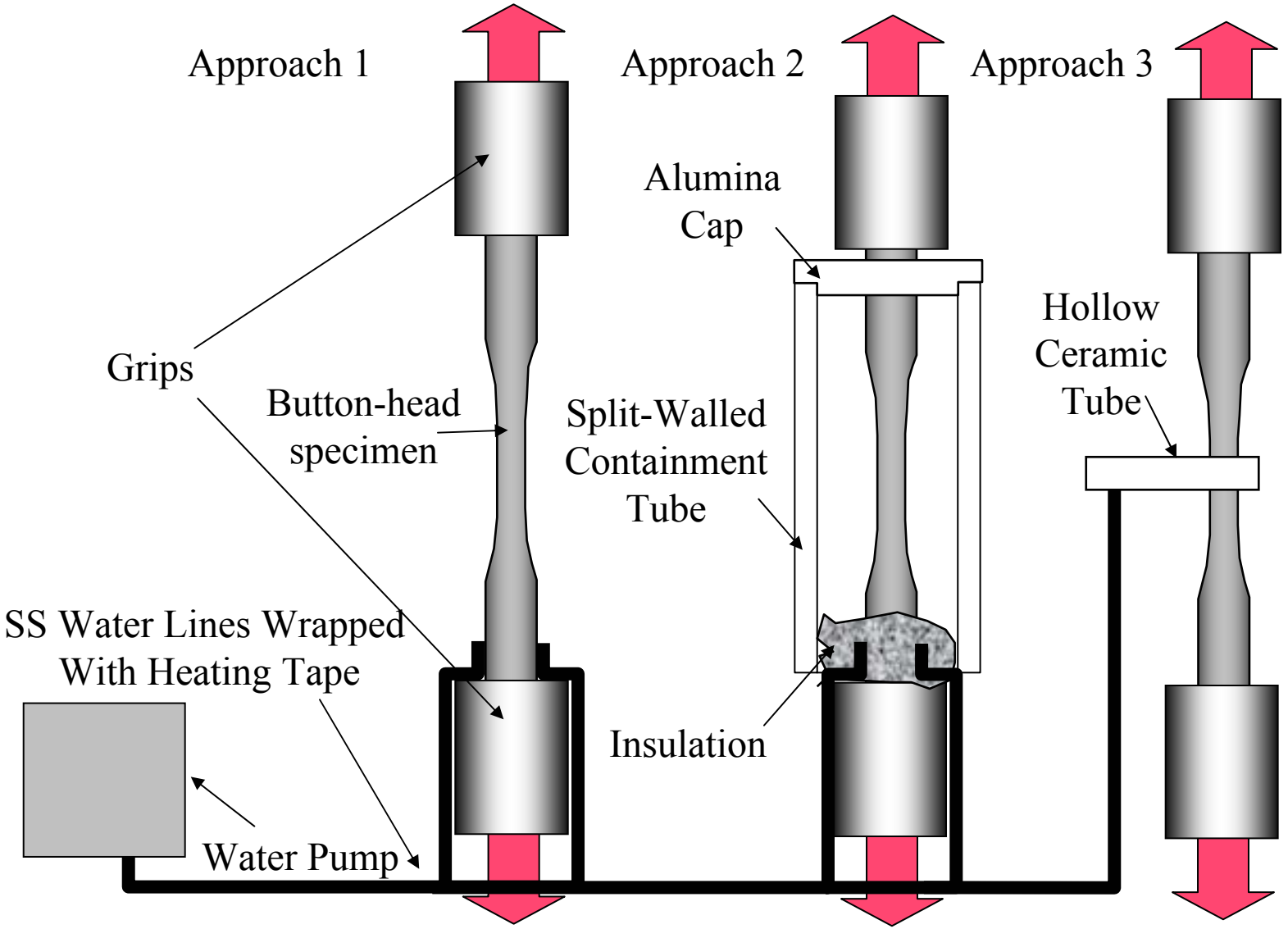


These Data are Ultimately used for Component Life Prediction





Emphasis is Currently being Placed Upon Characterizing Environmental Effects

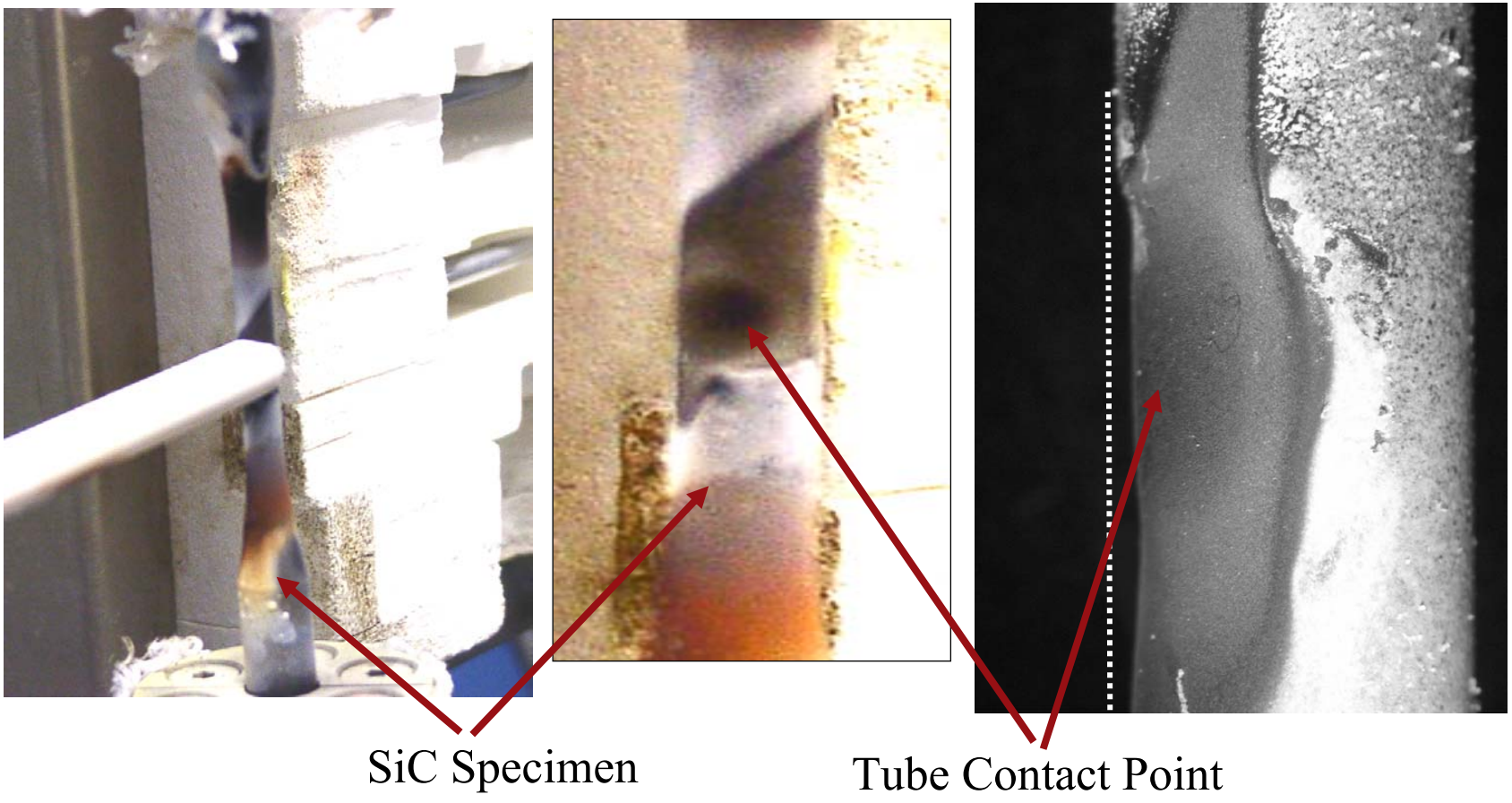


Objective of Environmental Testing

- **Evaluate the Effects of Water Vapor Upon the Strength and Creep Rupture Behavior of Uncoated Silicon Nitride Ceramics**
- **Evaluate the Effects of Environmental Barrier Coatings (EBCs) upon the Mechanical Behavior of these Structural Ceramics**
- **Examine the Effects of Mechanical Loading on the Mechanical Integrity of the EBC**
  - A Miniature Pull Test Based on the ASTM Adherence Test for Thermal Barrier Coatings will be used to Evaluate Adherence

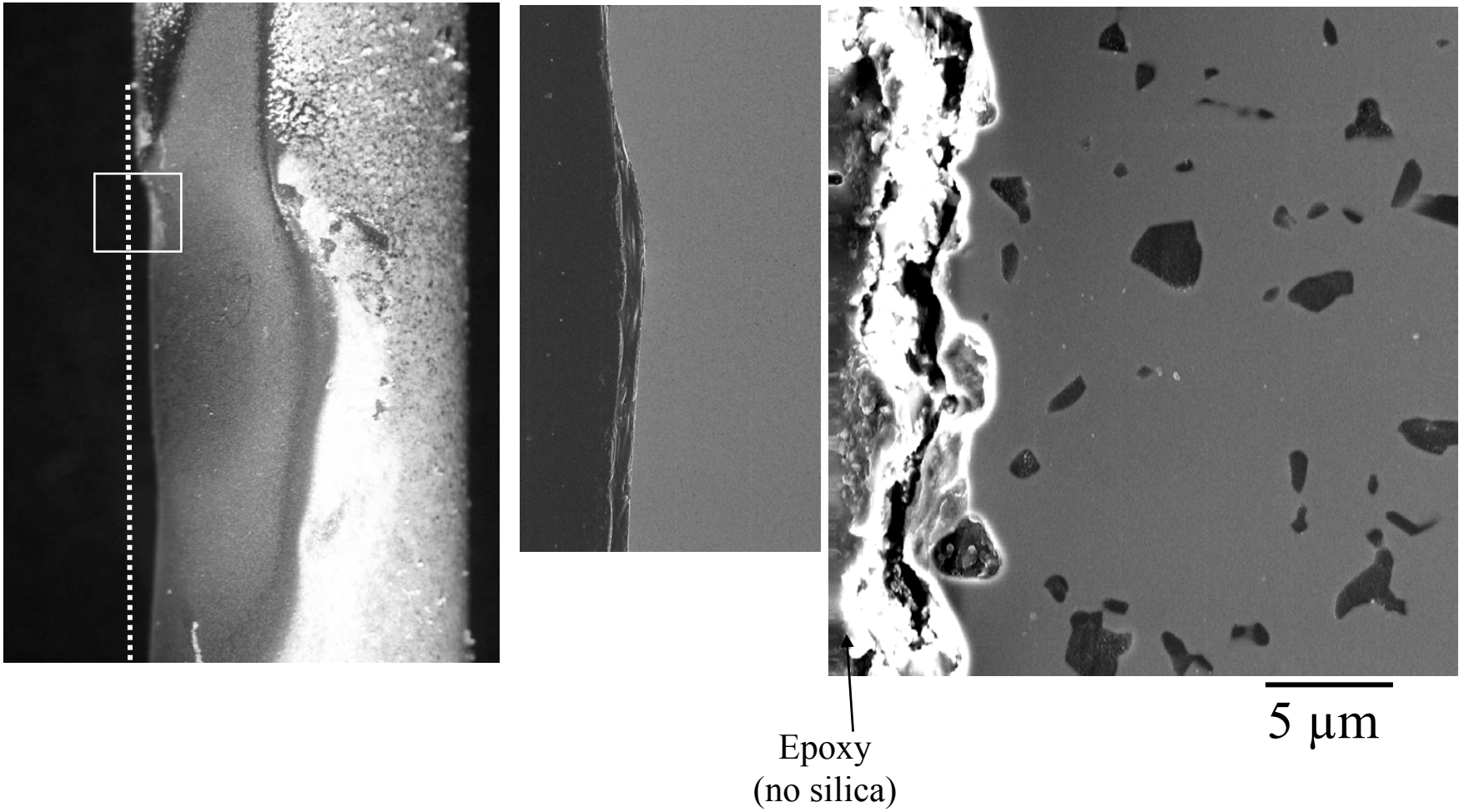
Approach 3 Yields Very Extensive Recession

- **SA SiC 1200°C 500 h with Water Vapor Specimen 291**



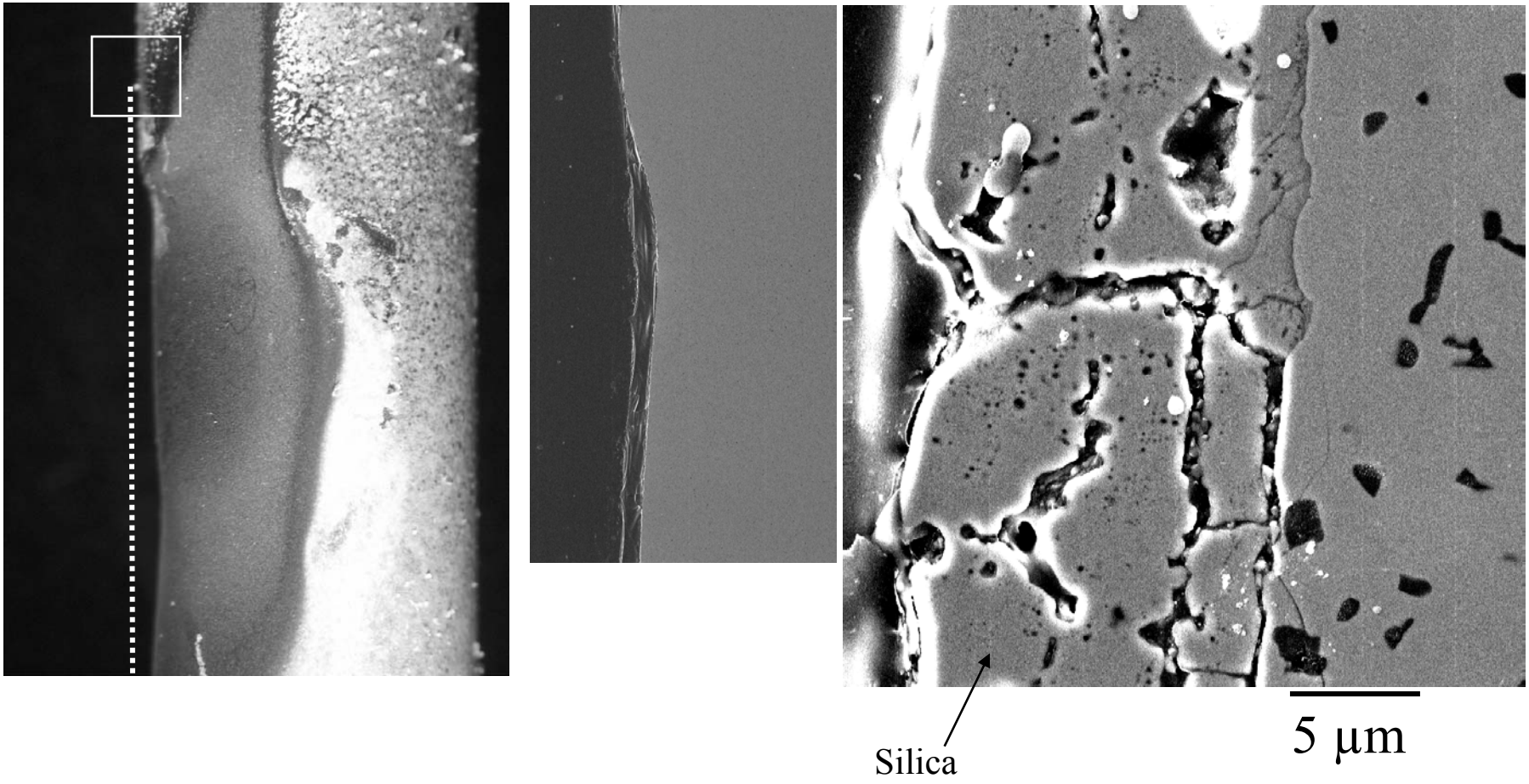
Approach 3 Yields Very Extensive Recession

- **SA SiC 1200°C 500 h with Water Vapor Specimen 291**



Approach 3 Yields Very Extensive Recession

- **SA SiC 1200°C 500 h with Water Vapor Specimen 291**



Environmental Effects

List of Accomplishments
Environmental Effects

- **Established extensive facilities for evaluating environmental stability of ceramics for gas turbine applications**
  - High-pressure, high-temperature steam rig (Keiser rig)
  - High-pressure, high-velocity burner rig
  - Microturbine Test Facility
  - GE Shroud rig

- **EBC development activities are now underway**
  - Evaluate new systems and deposition techniques
  - Improve durability of existing EBC systems for SiC-SiC composites
  - Adapt existing EBC systems for SiC-SiC composites to non-oxide monolithic ceramics

This Effort Was Initiated To Address Combustor Characterization Needs Arising After Chevron Engine Test

Arco operating ceramics Centaur to evaluate actual field service

By Irwin Stambler

Ceramics redesign, to uprate 4.1 MW Centaur to 5.2 MW and 31.2% efficiency at 2050°F firing temperature, should be available in kit form for factory retrofitting by 1999.

Earlier this year, in May, Arco Western Energy started in-service field tests of a Solar gas turbine fitted with ceramic hot section components. The test project, with over 800 operating hours as of June 25th, is located at Arco's oil field site near Bakersfield, California.

Test engine is a Centaur 50S operating on natural gas fuel. This is a stan-

1120°C (2050°F) for ISO base output increase to 5217 kW and over 5.5% points increase in thermal efficiency. To run at this rating for 4000 hours to prove durability.

The Arco project is a key milestone in the U.S. Dept. of Energy supported Ceramic Stationary Gas Turbine program. CSGT goal is to develop and

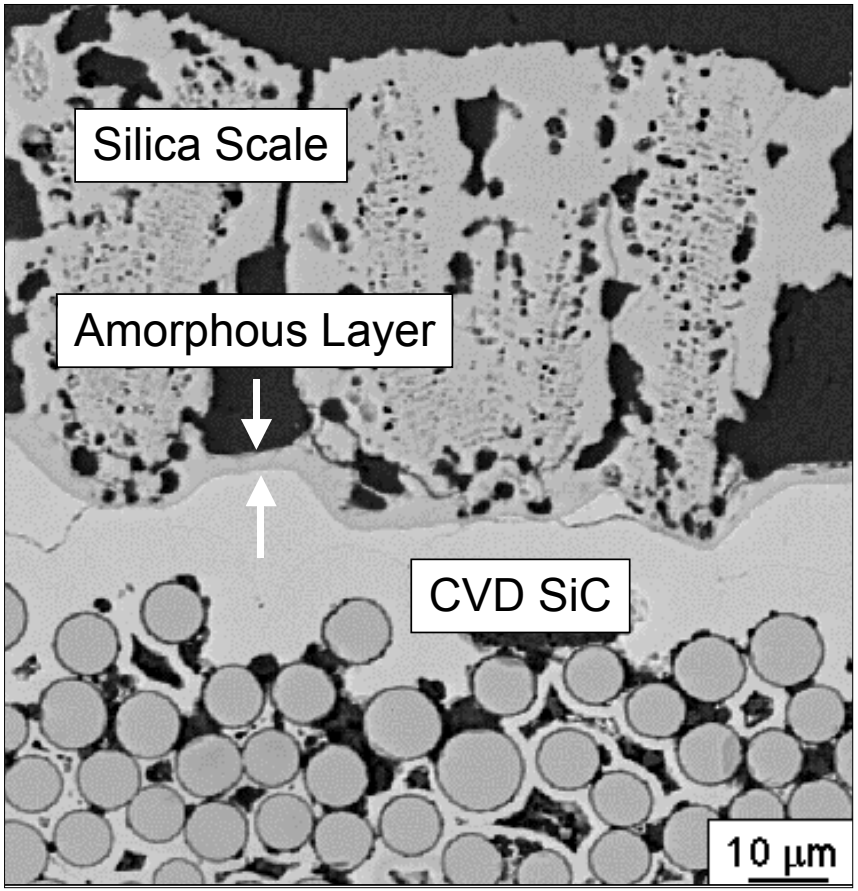
Two Tube Keiser Rig

To Date A Total of 10 Runs all Conducted at 1315°C, 10atm Total Pressure, and Either 0.3atm or 2atm H2O Have Been Completed for the Silicon Nitride Microturbines Work. This Represents ~160 Specimens of 3 Silicon Nitride Compositions Each Being Exposed for 2000 h.

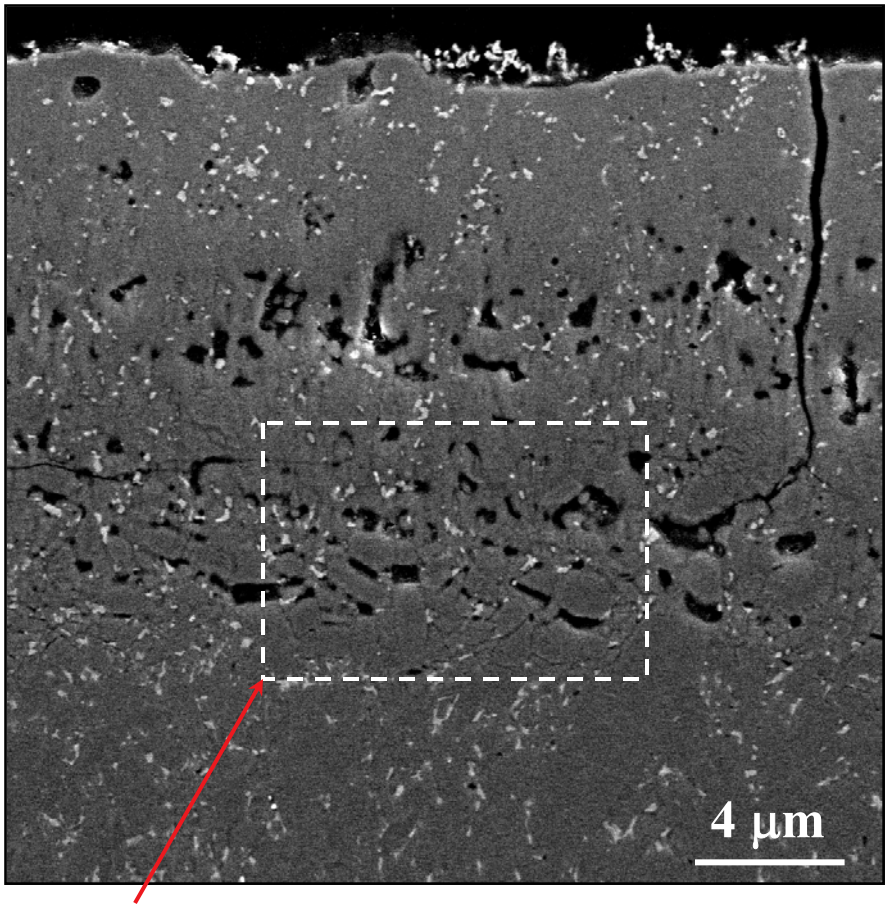
- Systems Consisting of Furnace, Power Supply, and Gas Supply
  - Hot Zone 10 in wide by 16 in Long
  - Each Furnace Can Hold 6 3.5 in Dia Tubes
- Tubes are Inserted Vertically into Top of Furnace
  - Flange on Open End of Each Tube Provides a Means of Support and Sealing Surface for Gas-Tight Seal
- Pressure, Composition, and Flow Rate of Test Gas can be Selected
  - Temperature as high as 1550°C
  - Gas pressures as high as 20.4 atm (300 psig)
  - Steam composition as much as 100% of the gas

Keiser Rig has been used to Establish the Environmental Stability of Uncoated Ceramics

SiC-SiC Composite



Silicon Nitride



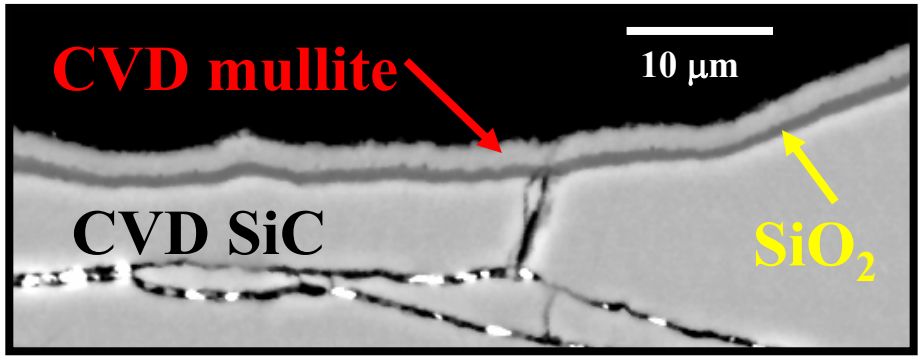
Subsurface damage zone formation accompanied with intergranular cracking

Keiser Rig is Currently Being Used to Evaluate the Effectiveness of EBCs

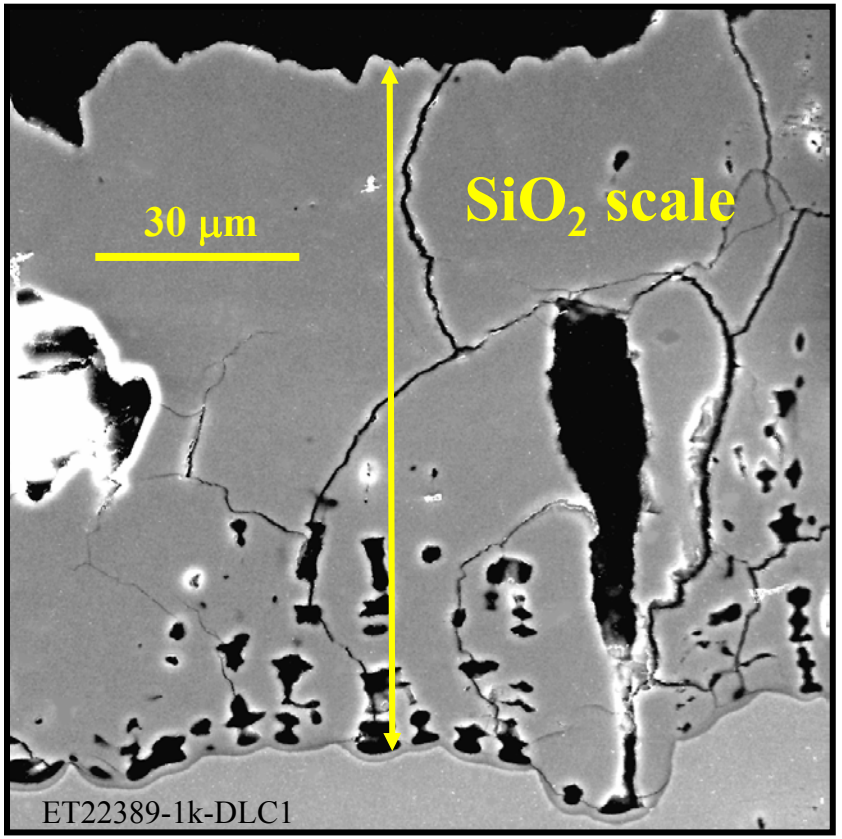
ORNL steam rig test: 1204°C, 500-h, 10 atm, 15% H_2O

- Bare SiC: SiO2 thickness = 90 - 120 mm
- CVD mullite: SiO2 thickness = 1- 3 mm
- Crystalline, high-purity CVD mullite was stable in high pressure steam

Mullite-coated CVD SiC



Bare CVD SiC



ORNL's Microturbine Recuperator Test Facility

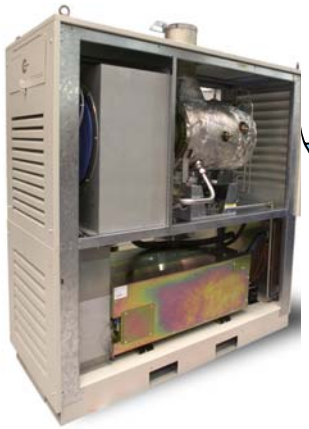
HAYNES International

SPECIAL METALS

partners

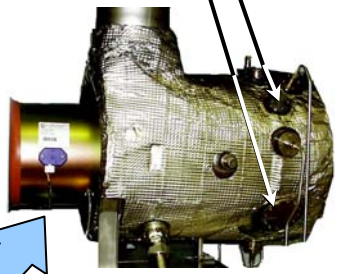
IR

Capstone



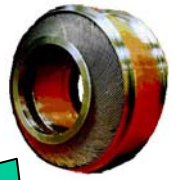
modified 60 kW
Capstone microturbine

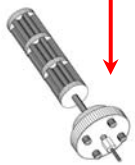
access ports for
sample exposure



maximum recuperator
inlet temperature: 843°C

annular
recuperator

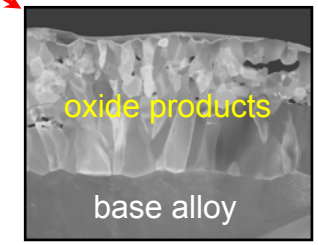




sample holder
with candidate
alloys

mechanical
evaluation

$4Fe + 3O_2 \rightarrow 2Fe_2O_3$
corrosion
analysis



chemical & microstructural
characterization

- ***screening and evaluation of candidate alloys for the next generation of microturbines.***
- ***Effects of stress and temperature on durability***
- ***Test specimens are positioned at the entrance of the recuperator***

Technical Contact:
Edgar Lara-Curzio
(865) 574-1749
laracurzioe@ornl.gov

Component Characterization

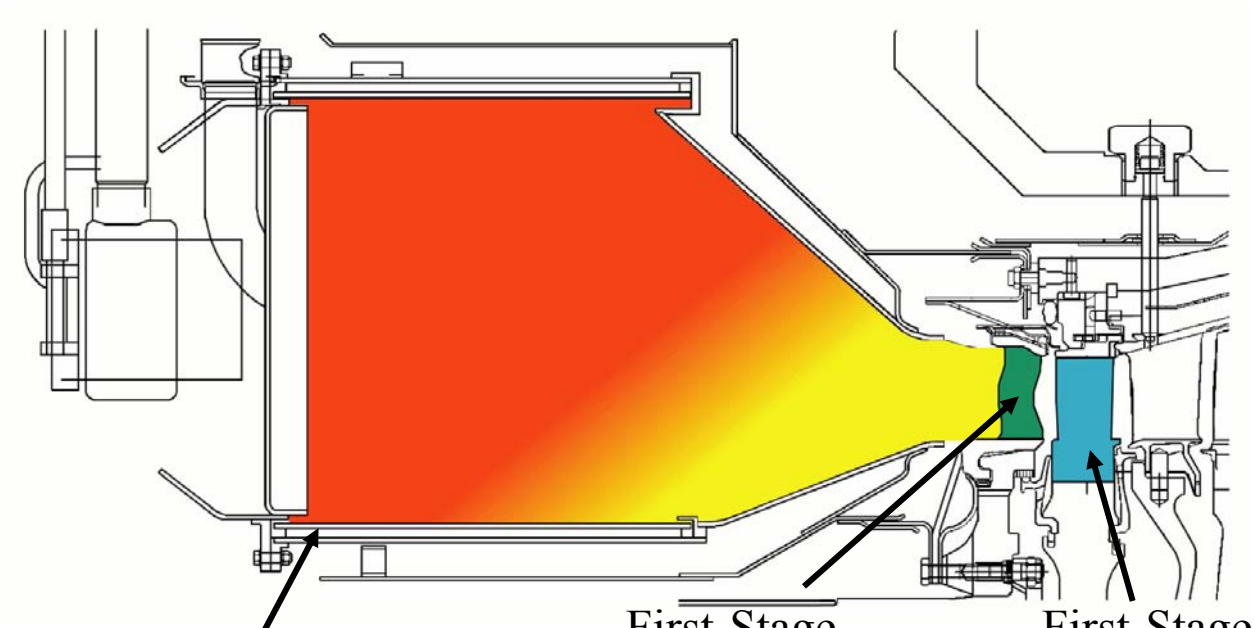
List of Accomplishments
Component Characterization

- **Provided characterization support to Solar Turbines in their Ceramics for Stationary Gas Turbines Program**
  - Database generation
  - Characterization of silicon nitride airfoils and ceramic composite combustor liners exposed in both test stands and extensive field tests
  - Evaluated the long-term reliability of EBCs applied to SiC-SiC combustor liners

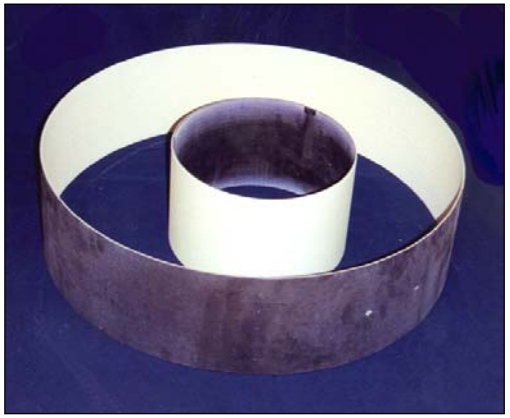
- **Provided extensive characterization support to Rolls Royce in their two series of engine tests involving silicon nitride vanes**
  - The results of this characterization effort established the baseline recession behavior of uncoated silicon nitride.
  - The characterization of the vanes in Test 2 provided the first ever field evaluation EBCs applied to a silicon nitride ceramic.

- **We are providing extensive mechanical property and component characterization support to UTRC in both their microturbine program and their EBC development program.**
  - This effort has been extremely useful for identifying processing-induced strength degradation in the complex shaped airfoils

CSGT Program Provided a Unique Opportunity to Evaluate Actual Components as a Function of Exposure Time



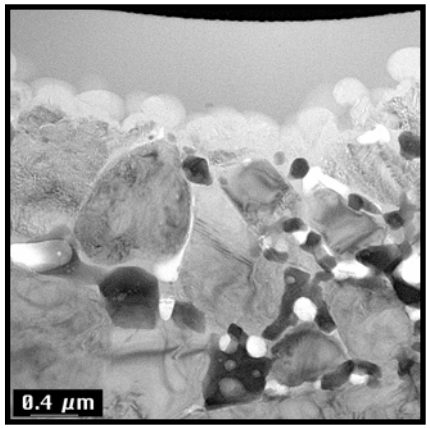
CFCC Combustor Liner

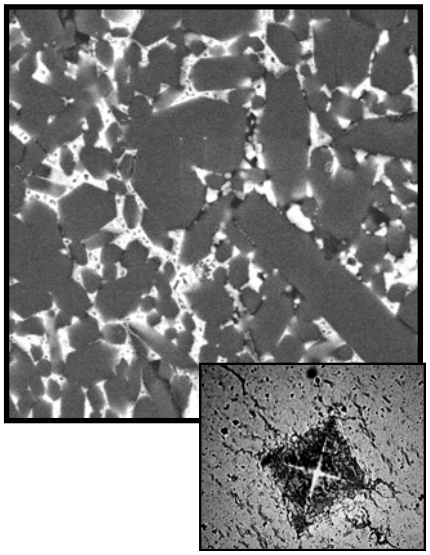


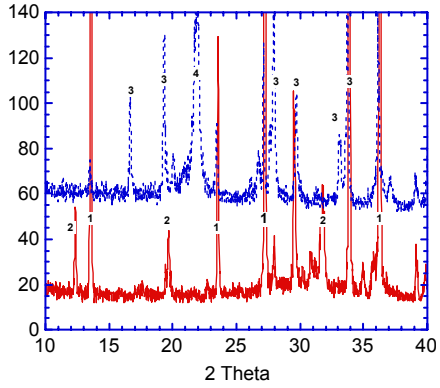
First-Stage Turbine Nozzle

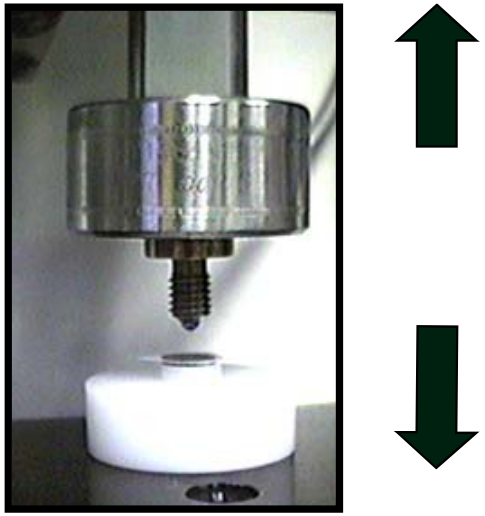
First-Stage Turbine Blade

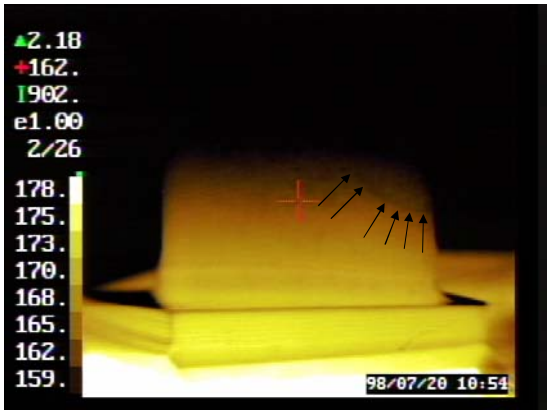
Types of Characterization



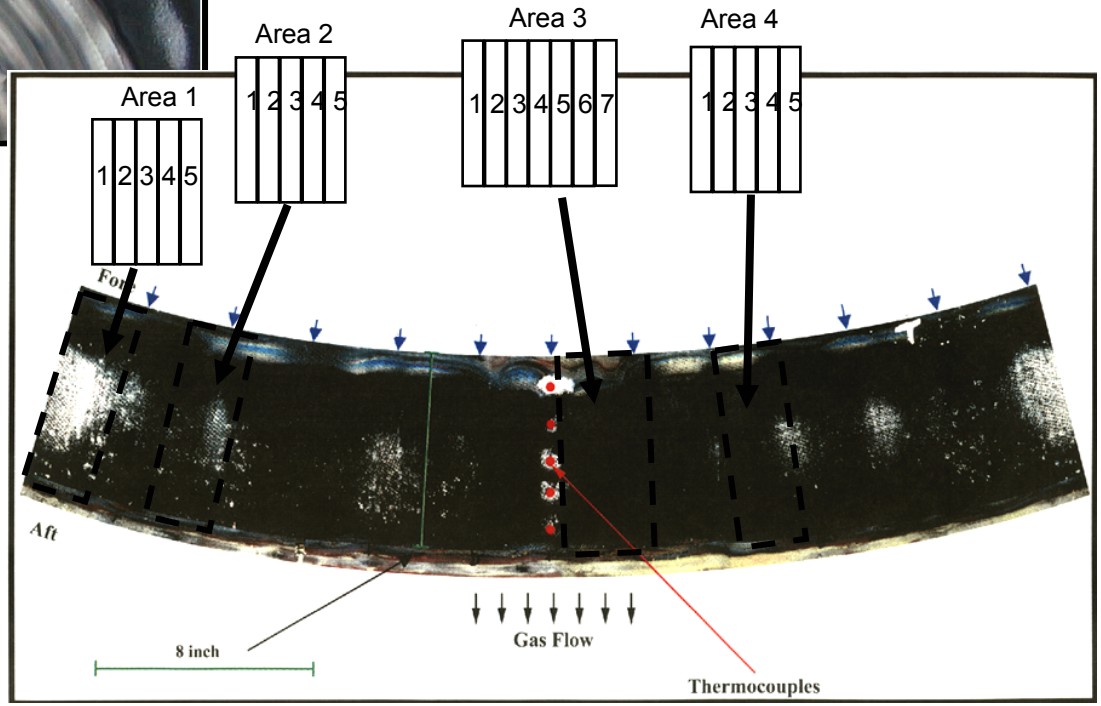




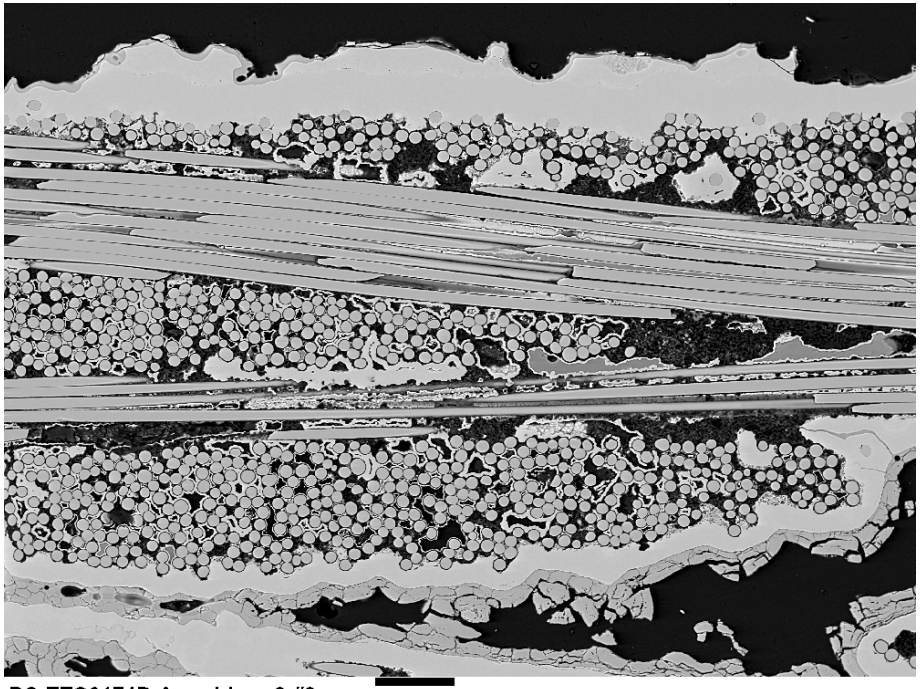




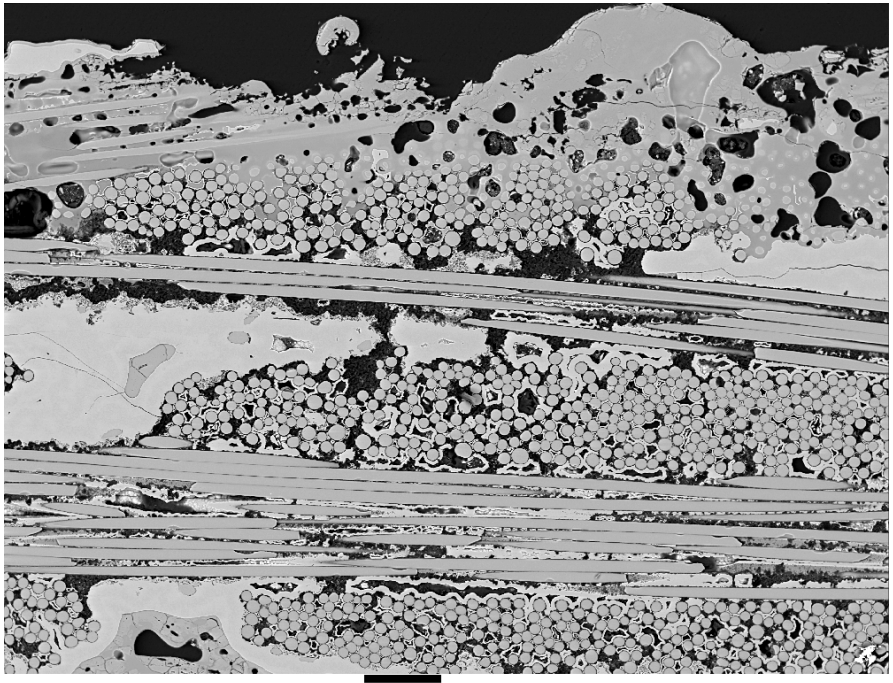
Inner Liner from Chevron Field Test was Examined



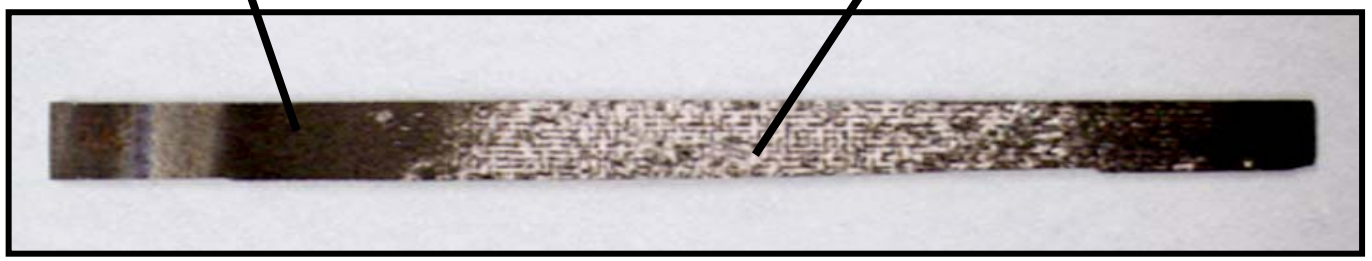
Seal Coat Recession Resulted in Eventual Breach



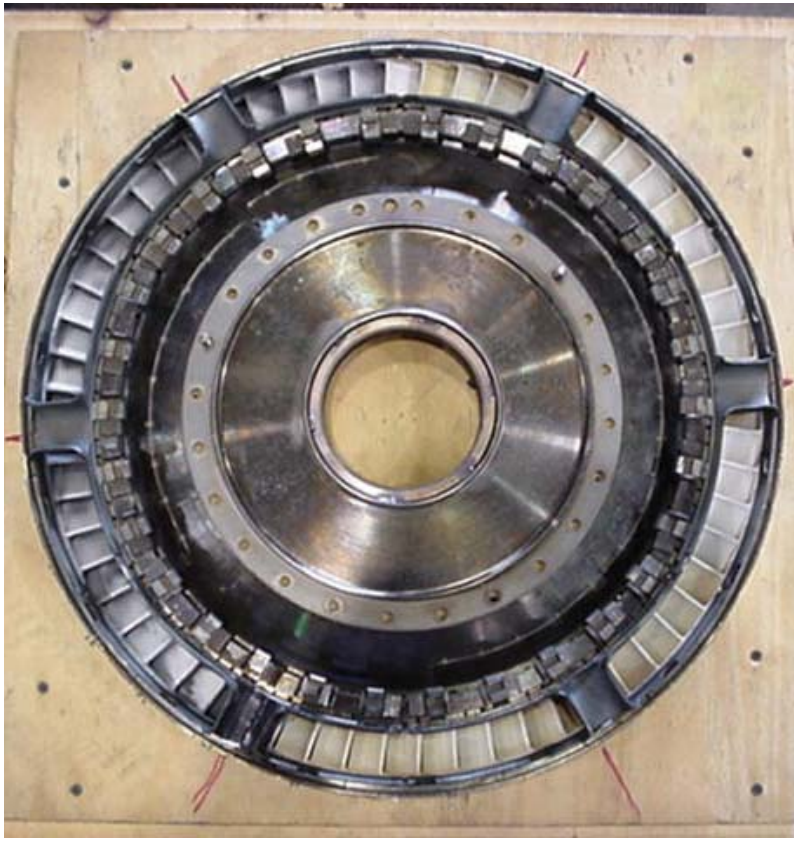
BS EZO3174D Arco Liner 2 #2 100µm



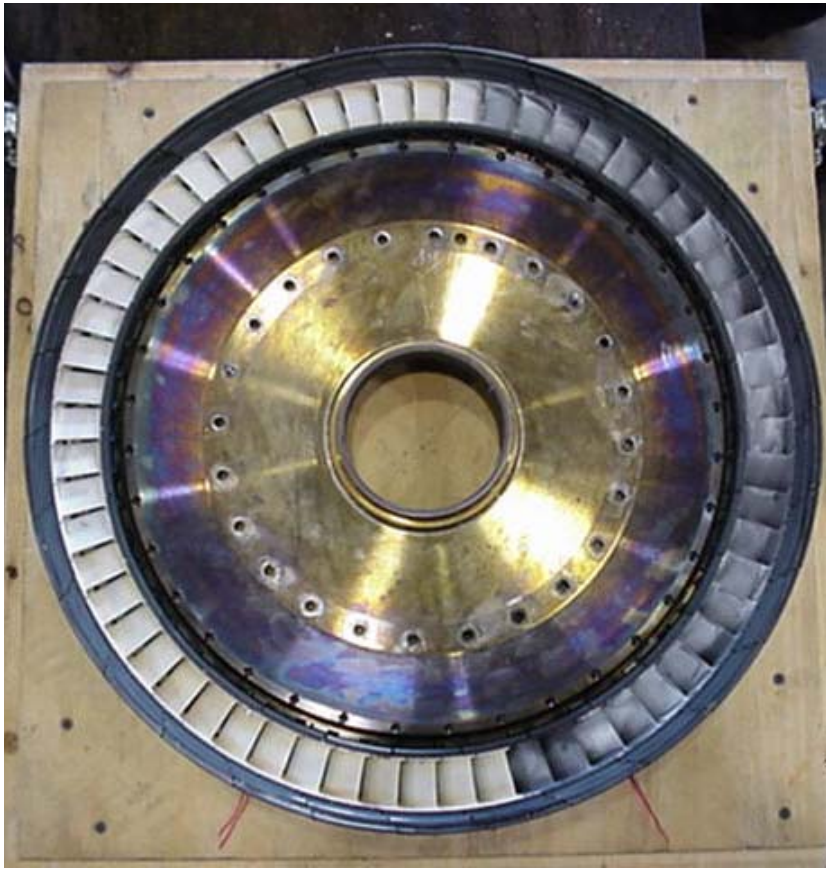
BS EZO3177F Arco Liner 2 #5 100µm



Over 60 Silicon Nitride Vanes were Evaluated during Two Field Tests Conducted by Rolls Royce

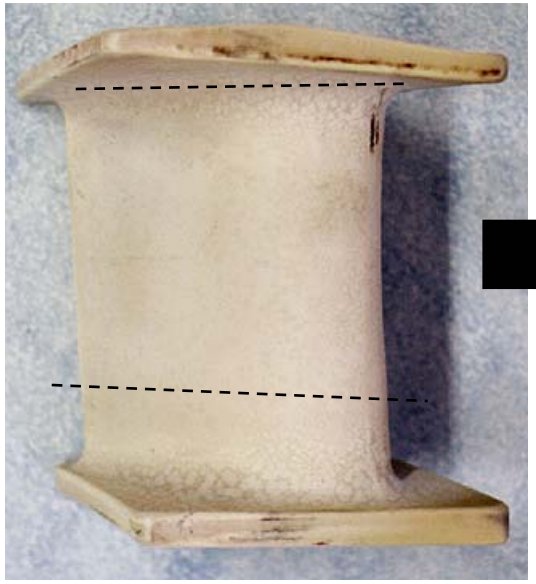


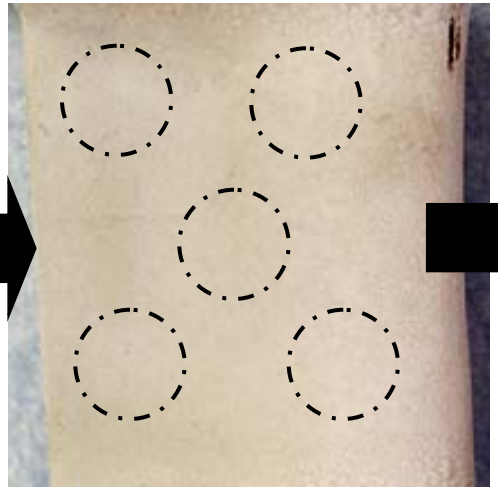
View of ceramic vane assembly forward looking aft



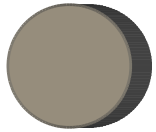
View of ceramic vane assembly aft looking forward

These Vanes were Subjected to Extensive Microstructural Analysis and Mechanical property Assessment





Core-Drill Cylinders
(5 mm dia)
Convex Surface

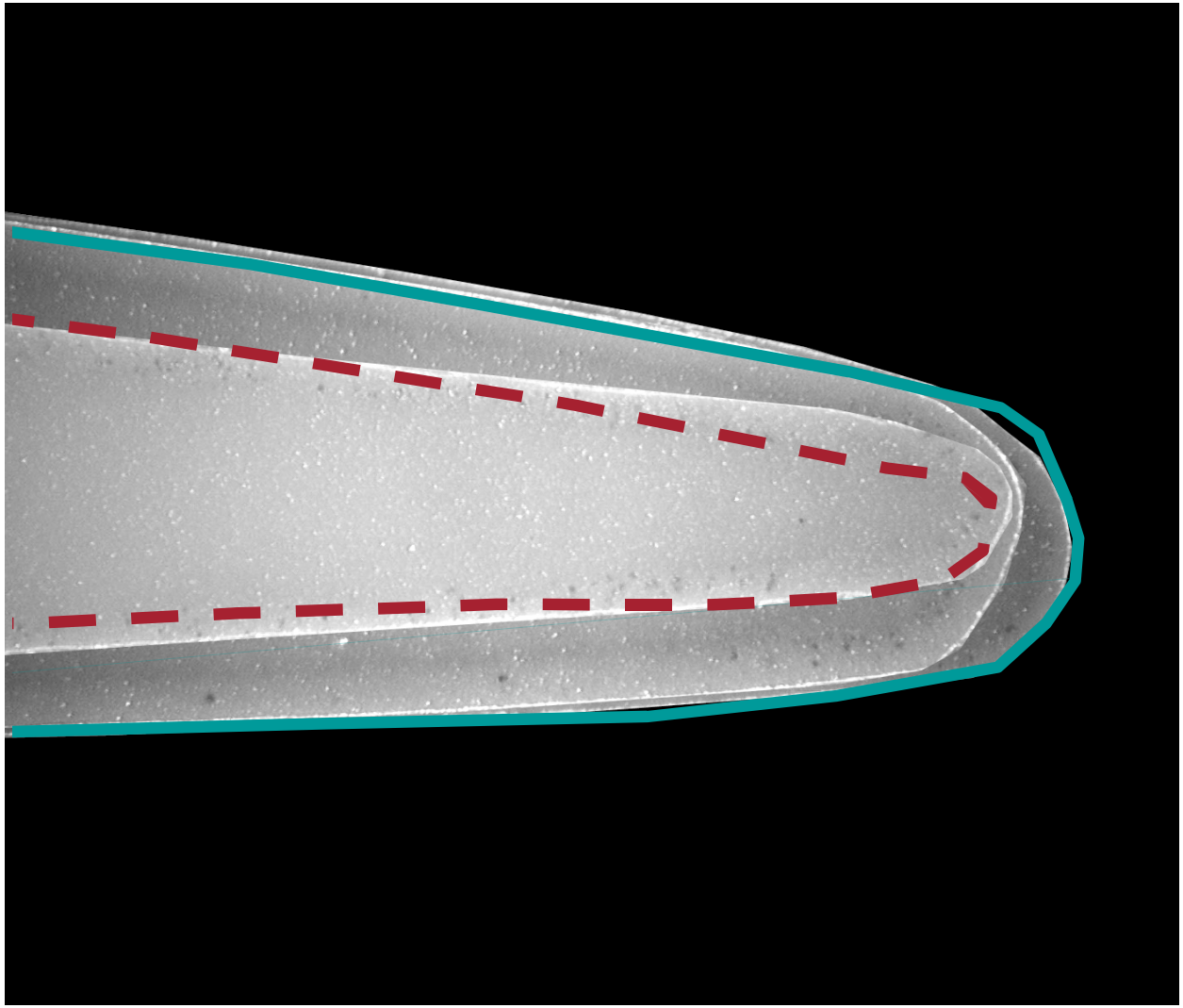


Machine from
Backside to 0.4 mm

Specimens for Biaxial Strength Measurement

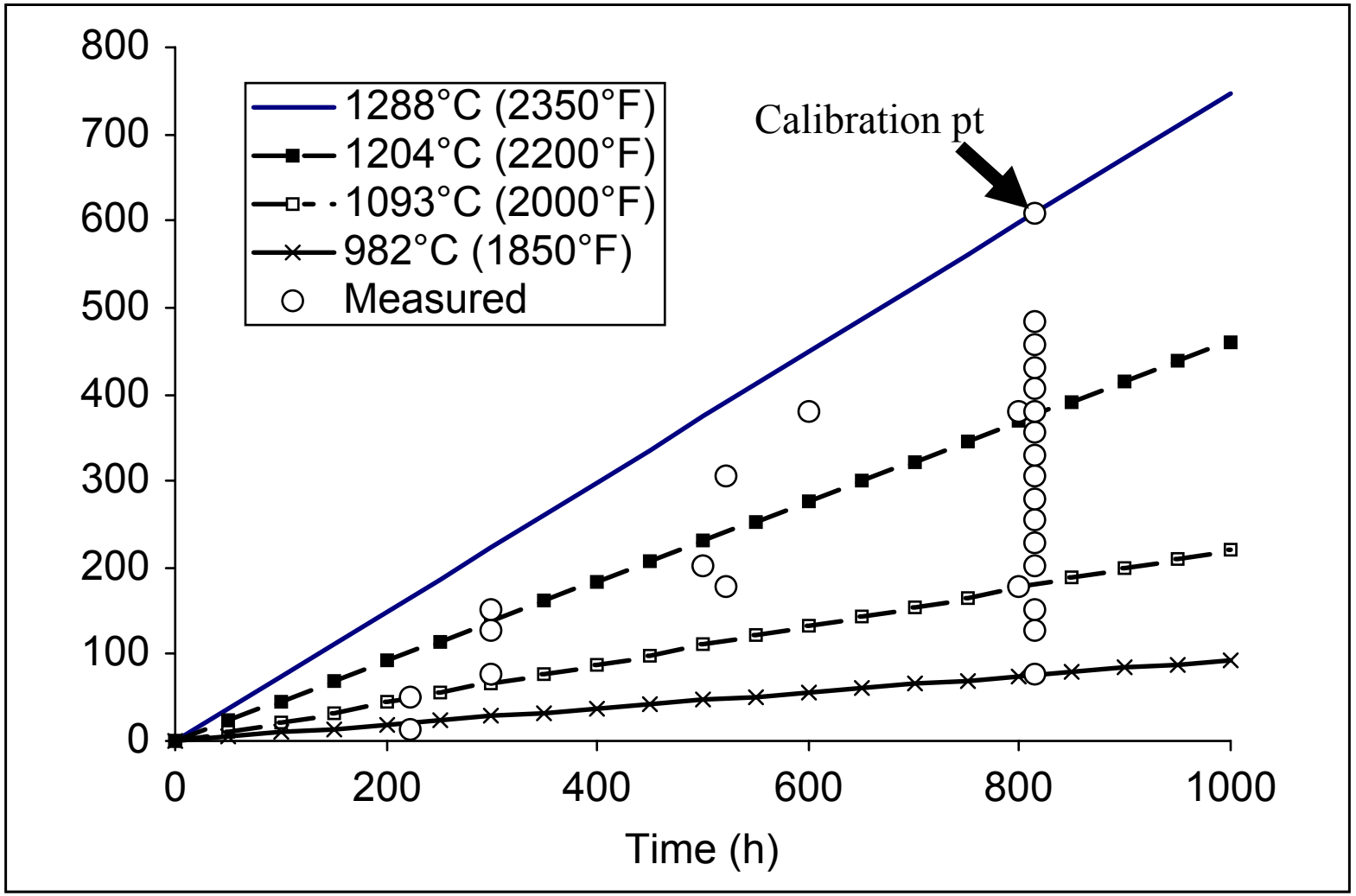
Sections for SEM

Calibrated Recession Model Also Described the Trailing Edge Recession of the Vane Subjected to the Highest Temperature



Cross-section-815 h/Vane 78

Envelope of Recession Rates Associated with Temperature Variations was in Excellent Agreement with Experimental Measurements



Component Characterization Activities are Currently Focusing on Microturbine Components

UTRC Kyocera SN281 ST5 Rotor Blank

S/N: UTRC0004-1, w/o: UTR0004 AA

Summary

- **Significant Accomplishments have been made in Three Areas**
  - Database and Life Prediction
  - Environmental Effects
  - Component Characterization

- **The Continued Success of this Project will Require Continued Interactions Between Team Members**